



PATENT APPLICATION

Docket No.: D498

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Title: Superheater Capillary Two-Phase Thermodynamic
Power Conversion Cycle System

SPECIFICATION

Statement of Government Interest

The invention was made with Government support under contract No. F04701-00-C-0009 by the Department of the Air Force. The Government has certain rights in the invention.

Reference to Related Application

The present application is related to applicant's copending application entitled Capillary Two-Phase Thermodynamic Power Conversion Cycle System S/N: xx/xxx,xxx, filed yy/yy/yy, by the same inventor, here incorporated by reference as there fully set forth.

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Field of the Invention

The invention relates to the field of thermodynamic power systems. More particularly, the present invention relates to two-phase thermal cycle systems, capillary devices, power generators, thermal condensers and liquid pumps.

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Background of the Invention

Thermodynamic power cycle systems have typically been used to generate useful work, such as in power generation systems. Thermodynamic power cycles have typically been used to turn heat input into the system into useful work as for power generation. Radioisotope elements, active nuclear and solar are used as heat sources for space power systems. Thermoelectric power conversion systems are currently used in deep space missions while photovoltaics are used for earth orbiting and some planetary missions. Radioisotope thermoelectric generators have thermodynamic efficiencies of seven to four percent or less while photovoltaics have overall efficiencies of typically 16% at end of life.

It is desirable to increase the efficiencies and power conversion levels of space based power generators. It is also desirable to directly produce AC power and thus eliminate the need for power converters for certain applications. It is also desirable to achieve high efficiencies and power conversion levels while the power conversion system operates at a lower maximum temperature relative to other power conversion systems. It is also desirable to have a power cycle that accepts heat input at different temperature levels. These different heat input temperatures allow for the recovery of waste heat used as heat input. It is also advantageous to have a power conversion system that is capable of storing energy using thermal energy storage media that is more efficient than batteries. It is also

1 desirable to have a power system capable of operating as a
2 bottoming cycle in a space-based cogeneration power system.
3 Space power systems that do not generate AC power
4 disadvantageously may require the use of an additional power
5 converter, such as in photovoltaic and thermoelectric systems.
6 Turbines have been used both terrestrially and in space to
7 generate AC power. Space based dynamic power conversion cycles
8 have been limited to single-phase Brayton and Stirling systems.
9 The overall thermodynamic efficiency of two-phase power
10 conversion systems, such as the Rankine system, is generally
11 greater than single-phase systems. Large terrestrial two-phase
12 Rankine cycle systems typically operate at over thirty percent
13 efficiency. Although the Rankine cycle has been used
14 extensively in terrestrial applications for power generation,
15 the Rankine power cycle has not been used in space applications
16 because of the difficulty and complexity required to manage a
17 two-phase power system fluid in micro gravity.

18
19 Rankine cycle systems are typically described using
20 conventional temperature and entropy graphs and functional
21 block descriptions. A typical Rankine system includes an input
22 heat source, a boiler, a superheater, a turbine, a condenser,
23 and a liquid pump. Heat is input into the boiler, the working
24 fluid gradually changes from liquid to vapor as heat is
25 received. That is, the Rankine cycle entropy extends from a
26 subcooled liquid point to a saturated vapor point during heat
27 addition. The heating in the boiler of a Rankine cycle system
28 provides the working fluid flow with an infinitesimally small

1 amount of heat input, which results in an infinitesimally small
2 change in the quality of the flow. In the boiler of a Rankine
3 cycle system, the vapor and liquid are carried together. The
4 boiler provides a phase change from liquid to vapor. The input
5 heat source heats the working fluid in the boiler generating
6 and providing saturated vapor, which is fed into the
7 superheater. The superheated vapor then spins the turbine for
8 providing output work, such as electrical power. The
9 superheater is used to ensure that the vapor entering the
10 turbine is superheated to a higher pressure and thus has no
11 liquid droplets in it to avoid liquid impingement with the
12 turbine blades while providing sufficient pressure and flow to
13 spin the turbine to generate the desired amounts of power. The
14 turbine provides low-pressure saturated vapor to the condenser.
15 The condenser provides a phase change from vapor to liquid. The
16 liquid is then pumped by the active pump into the boiler for
17 completing the cycle. The Rankine cycle disadvantageously
18 requires all input heat to be transferred to the work fluid
19 while at one pressure. Having the working fluid at constant
20 pressure during the heat addition process restricts the cycle
21 and limits the amount of low temperature heat that can be
22 added. Rankine cycle also disadvantageously uses a boiler to
23 add heat to the cycle flow. For terrestrial applications,
24 gravity is used to maintain the separation of liquid and vapor
25 in the boiler and at the active liquid pump. Maintaining this
26 separation without gravity, in space, is difficult and
27 typically makes Rankine power cycle systems unsuitable for
28 space applications.

1
2 Commercial loop heat pipes and capillary pumped loops have
3 been developed to passively control the dynamics and location
4 of liquid and vapor interface points in micro gravity. As such,
5 loop heat pipes and capillary pumped loops are commonly used
6 for the thermal control of spacecraft. To date, there are over
7 one hundred loop heat pipes and capillary pumped loops in
8 operation, on orbit, on spacecraft. The loop heat pipe as well
9 as the capillary pumped loop allows deployable condensers to be
10 used on spacecraft as part of a two-phase heat rejection
11 system. A loop heat pipe or capillary pumped loop includes a
12 capillary wick that facilitates flow from a low pressure point
13 to a high pressure point. The capillary wick is used to
14 pressurize and drive the loop heat pipe or capillary pumped
15 loop heat rejection system. Loop heat pipes and capillary
16 pumped loops have pumping capabilities orders of magnitude
17 greater than simple heat pipes. Loop heat pipes are being used
18 on commercial satellites and are described in U.S. Patent
19 5,743,325. The transport lines of the loop heat pipe or a
20 capillary pumped loop heat rejection system are typically made
21 from simple tubing that is bent and welded. Loop heat pipe and
22 capillary pumped loop systems use Aluminum, stainless steel and
23 other nickel based superalloys for use typically with ammonia
24 as the working fluid. Deployable condensers and flexible tubing
25 are used to configure the heat rejection system.

1 A capillary wick receives a saturated liquid. The liquid
2 wets the capillary wick. It is drawn through the capillary wick
3 because the working fluid molecules are attracted more to the
4 capillary wick material than they are to each other. The liquid
5 is also pushed through the capillary wick through
6 pressurization. The capillary wick provides the separation
7 between the high-pressure vapor and the low-pressure liquid.
8 Heat is input on the high-pressure side of the capillary wick
9 where the fluid is vaporized. Once liquid turns into vapor
10 through evaporation, the volume of the working fluid increases
11 orders of magnitude causing the pressure to increase on the
12 high-pressure side of the capillary wick. This increase in
13 pressure pushes the saturated vapor forward through the system.
14 The flow cannot go backwards toward the lower pressure
15 saturated liquid path because the pores in the capillary wick
16 are so small that a meniscus forms in them and acts as a
17 barrier to the high-pressure vapor. Capillary wicks with pores
18 sizes of about one micron are commercially available. Based on
19 the Laplace-Young equation, which is a function of pore
20 geometry and surface tension, and wetting angle and using
21 ammonia as a working fluid, a capillary wick with one-micron
22 pores can sustain a pressure differential of approximately ten
23 psi.

24
25 The loop heat pipe is similar to a capillary pumped loop,
26 but having different placement of the fluid reservoir. In the
27 loop heat pipe, the reservoir is attached to the evaporator. In
28 the capillary pumped loop, the reservoir is remotely located

1 with respect to the evaporator. A loop heat pipe or capillary
2 pumped loop generates fluid pumping energy through the addition
3 of heat, from an input heat source, onto a capillary wick.

4
5 Two-phase power systems are the most efficient types of
6 power systems. The two-phase liquid vapor interface management
7 problem is solved for loop heat pipe and capillary pumped loop
8 thermal control capillary devices. Although two-phase systems
9 have been used extensively on earth, two-phase power systems
10 have not been used in space because of an inability for
11 controlling the interface between the two-phases in micro
12 gravity during steady state operation as well as transient
13 operation. These and other disadvantages are solved or reduced
14 using the invention.

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Summary of the Invention

An object of the invention is to provide a two-phase thermal cycle for use as a thermodynamic power system pressurized by a capillary device, superheater and liquid pump.

Another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for driving a turbine for providing output energy.

Yet, another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for generating power during power generation.

Yet, another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for generating power at high efficiencies while operating at low temperatures.

Yet, another object of the invention is to provide a two-phase thermal cycle for use in a thermodynamic power system pressurized by a capillary device, superheater and liquid pump for generating power using heat input at varying pressures and temperatures.

1 Yet another object of the invention is to provide a two-
2 phase thermal cycle for use in a thermodynamic power system
3 pressurized by a capillary device, superheater and liquid pump
4 for generating power using low grade or waste heat for recovery
5 as part of the total heat input.

6
7 Yet another object of the invention is to provide a two-
8 phase thermal cycle for use in a thermodynamic power system
9 pressurized by a capillary device, superheater and liquid pump
10 for generating power from a nonsteady heat source operating
11 using stored thermal energy.

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13 Yet another object of the invention is to provide a two-
14 phase thermal cycle for use in a thermodynamic power system
15 pressurized by a capillary device, superheater and liquid pump
16 for generating power as a bottoming cycle in a cogeneration
17 power system.

18
19 A further object of the invention is to provide a two-
20 phase thermal cycle for use in a thermodynamic power system
21 pressurized by a capillary device, such as a loop heat pipe,
22 superheater and liquid pump.

23
24 Yet, a further object of the invention is to provide a
25 two-phase thermal cycle for use in a thermodynamic power system
26 pressurized by a capillary device, such as a capillary pumped
27 loop, superheater and liquid pump.

1 Another object of the invention is to provide a two-phase
2 thermal cycle for use in a thermodynamic power system
3 pressurized by a capillary device providing an instantaneous
4 transition from liquid to vapor phase of the working fluid
5 using input heat.

6
7 Still a further object of the invention is to provide a
8 two-phase thermal cycle for use in a thermodynamic power system
9 pressurized by a capillary device for generating power during
10 power generation with improved efficiency using an in-line
11 superheater, a preheater, and a liquid pump.

12
13 The system is directed to a two-phase thermodynamic power
14 cycle system that converts heat energy to work particularly
15 useful in space power systems. The system uses a capillary wick
16 of a capillary device that uses input heat to generate high-
17 pressure saturated vapor. The high-pressure saturated vapor is
18 kept separate from low-pressure saturated liquid. This
19 capillary wick facilitates the flow transition from high
20 pressure, high temperature, saturated liquid to high-pressure,
21 saturated vapor, instantaneously, providing effective
22 separation between liquid and vapor and being a passive pump.
23 The system solves the problem of two-phase fluid management in
24 micro gravity by simplifying the two-phase thermodynamic cycle
25 system using a capillary device, such as loop heat pipe or a
26 capillary pumped loop, for two-phase fluid control. The system
27 is a power conversion unit that receives heat from a heat
28 source to passively drive the capillary action. The capillary

1 action passively separates liquid from vapor and pressurizes
2 the flow so that high-pressure saturated vapor can enter the
3 superheater of the system. Saturated high-pressure vapor flows
4 into the superheater through diode valves. These valves allow
5 the flow to enter the superheater but prevent the flow from
6 flowing back towards the evaporator. Once the pressure in the
7 superheater equals the pressure of the high pressure, saturated
8 vapor, flow into the superheater stops. Heat addition to the
9 high-pressure, saturated vapor continues until the vapor
10 reaches the desired superheated vapor state. Once the vapor
11 reached the desired state of superheat, the superheater control
12 valve is opened releasing superheated vapor that flows to the
13 turbine. Vapor flows isentropically through the turbine where
14 work is taken out of the flow. Multiple superheater stages can
15 be used. The pulsing of these multiple stages can be staggered
16 in order to obtain a flow that is steadier than simple pulses.
17 The superheater can be one leg or several parallel tube legs,
18 for example each leg tens of feet long, bent in a serpentine
19 manner, attached to a heat source. Each leg of the superheater
20 has a controllable diode input valve and controllable exit
21 valve. The flow exits the turbine as low-pressure, saturated
22 vapor and enters the condenser. The vapor condenses in the
23 condenser and leaves as low pressure saturated liquid. The
24 condenser can be one tube, for example, tens of feet long, bent
25 in a serpentine manner, and attached to a condenser panel. The
26 condenser tubing can also be fabricated in a conventional
27 parallel arrangement. Liquid enters a pump where work is put
28 in and the liquid is pressurized isentropically to a high

1 pressure, low temperature, subcooled liquid. The high pressure,
2 low temperature, subcooled liquid flows through the liquid
3 preheater and leaves as a high pressure, high temperature,
4 saturated liquid which enters the evaporator to repeat the
5 cycle. The liquid preheater can be one tube, for example, tens
6 of feet long, bent in a serpentine manner, and attached to a
7 heat source. The preheater tubing can also be fabricated in a
8 conventional parallel arrangement.

9
10 The system preferably includes an evaporator comprising a
11 capillary device having a capillary wick for receiving input
12 heat and providing a phase change, a vapor accumulator to
13 dampen and prevent mass flow oscillations from effecting the
14 operation of the evaporator, a superheater receiving input heat
15 and providing further increased pressure and temperature to the
16 high pressure saturated vapor, a turbine for providing power,
17 a condenser for radiating heat, a liquid pump for increasing
18 the pressure of the low pressure saturated liquid and a
19 preheater for increasing the temperature of the high pressure,
20 low temperature, subcooled liquid.

21
22 The loop heat pipe or capillary pumped loop, collectively
23 referred to as capillary devices, are preferably used in
24 combination with a vapor accumulator, superheater, turbine,
25 liquid pump and liquid preheater to produce output power. A
26 turbine can be placed in the thermal cycle loop for providing
27 output power during power generation . The system includes
28 necessary tubing for transport of the working fluid between

1 components, through the superheater, condenser, liquid pump and
2 liquid preheater. The system can be used for small terrestrial
3 solar, gas, heat recovery and/or geothermal as heat sources for
4 power generation stations with an efficiency potentially higher
5 than photovoltaic and basic Rankine systems. High grade AC
6 power can be generated directly using a turbine-rotating
7 machine to generate power.

8
9 The system preferably uses spacecraft thermal control
10 technology, including loop heat pipes and capillary pumped
11 loops, by combining these capillary devices with a turbine,
12 superheater, liquid pump and liquid preheater. Loop heat pipes
13 and capillary pumped loops are used for thermal control
14 applications on spacecraft for a variety of reasons including
15 that these devices allow for system integration with flexible
16 lines, and enable deployable condensers. The system provides a
17 two-phase dynamic power system suitable for space application.
18 The system can be cost efficiently built as a system to
19 generate power using the waste heat as a portion or all of the
20 input heat from a spacecraft or waste heat from another dynamic
21 or static power converters in a cascaded manner. This waste
22 heat or cascaded system will yield a space power system with an
23 overall efficiency of well over thirty percent to provide a
24 spacecraft with significantly more power while enabling ion
25 propulsion and increased payload capabilities.

26
27 The system obtains pressurization of high pressure,
28 saturated vapor flow occurring at the capillary wick. In the

1 thermal cycle of the system, high pressure saturated vapor and
2 high pressure, high temperature saturated liquid points are
3 separated during the capillary heat source input phase of the
4 cycle. That is, the working fluid abruptly changes from a
5 saturated high pressure, high temperature saturated liquid to
6 high-pressure saturated vapor. During heat addition, high
7 pressure, high temperature, saturated fluid changes directly to
8 high pressure, saturated vapor and the quality of the flow goes
9 directly from all liquid to all vapor. The thermal cycle
10 process jumps from the high pressure, high temperature,
11 saturated liquid point to high-pressure, saturated vapor point.
12 This entropy jump on the temperature and entropy diagram
13 mirrors the physics at the liquid vapor interface of the
14 capillary wick, where high pressure high temperature saturated
15 liquid is physically in contact, but separated from high
16 pressure saturated vapor. When an infinitesimally small amount
17 of heat is added at the saturated vapor side of the capillary
18 wick, an infinitesimally small amount of high pressure,
19 saturated vapor will be formed. At the vapor liquid interface
20 of the thermal cycle, liquid and vapor are in contact but
21 separated across the capillary wick. The capillary wick can be
22 built using different types of materials and in different
23 geometries. The evaporator of a loop heat pipe or capillary
24 pumped loop contains a capillary wick. The loop heat pipe
25 evaporator includes a primary capillary wick and a secondary
26 wick, the reservoir, the liquid input line, and vapor exit
27 line, as well as the housing for the primary capillary wick.
28 The capillary wick receives heat from an input heat source.

1 Conventional loop heat pipe or capillary pumped loop
2 evaporators can be used.

3
4 The superheater is used to significantly increase the
5 pressure of the vapor by adding additional heat bringing it to
6 a superheated state. Although the vapor flow from the
7 evaporator flows through the accumulator into the superheater,
8 the evaporator is not exposed to the high pressures generated
9 in the superheater. This is accomplished by pulsing the
10 superheater using controllable diode and control valves. This
11 allows for significantly higher-pressure, superheated vapor to
12 flow into the turbine for power generation. This also insures
13 that the working fluid flowing into the turbine is all vapor.
14 In the preferred form of the invention, the superheater,
15 disposed after the capillary wick and accumulator, is connected
16 to a higher temperature heat source compared to the evaporator
17 and liquid preheater heat sources. The superheater used in
18 combination with a preheater and with a liquid pump that are
19 both disposed before and the capillary wick allow for improved
20 efficiency by increasing the operating range of the system.
21 The flow is high-pressure saturated vapor that flows into the
22 superheater. The superheater is preferably a heat exchanger
23 that must interface with a heat source that is maintained at a
24 higher temperature than the capillary wick. In practice, the
25 superheater is a plurality of heat exchanging tubular chambers
26 through which the cycle working fluid flows and is heated. Flow
27 at the entrance to these chambers is checked by a diode valve,
28 only allowing flow in. The exit to these chambers is checked by

1 a control valve, operated so that the chamber pulses. This heat
2 chamber can be attached to an external heat source. The flow is
3 then heated for staggered release. Using multiple chambers, a
4 quasi-continuous superheated vapor flow can be achieved for
5 driving the turbine. The superheater is used to increase the
6 efficiency of the cycle and to heat the working fluid to ensure
7 that no condensed droplets enter the turbine. The impingement
8 of droplets on the turbine will eventually cause the turbine to
9 erode. The superheated vapor is passed through the turbine.
10 Thermal energy storage material such as a phase change material
11 can be connected to the superheater to store energy so that the
12 superheater can operate constantly even if the heat source is
13 not steady such as solar heating in Low Earth Orbit. This
14 thermal energy storage material can be a single phase metal
15 such as beryllium, or a two phase such as lithium or a molten
16 salt that changes phase at the superheater operating
17 temperature.

18
19 The superheater is used to increase power output of the
20 device by adding heat into the flow. The liquid pump is used to
21 increase the pressure of the condensed liquid so that the
22 liquid returning to the evaporator is at a pressure close to
23 that of the high-pressure saturated vapor. Using the
24 superheater and liquid pump the pressure difference, from
25 lowest pressure to highest pressure in the cycle can be
26 increased without regard to the maximum sustainable pressure
27 differential across the capillary wick. The capillary wick is
28 isolated from these extreme pressures and is mainly required to

1 separate liquid and vapor. A small pumping capability is
2 required only to move the high-pressure saturated vapor through
3 the vapor accumulator into the superheater. The liquid
4 preheater is used to reduce the amount of evaporator input
5 energy required. With a liquid pump incorporated into the power
6 cycle, low operating temperatures, just above the freezing
7 point of the working fluid, are possible in the condenser.
8 After this low pressure, saturated fluid from the condenser
9 passes through the liquid pump it is significantly subcooled.
10 If this fluid were returned directly to the evaporator without
11 passing through the liquid preheater, it would require that a
12 significant amount of additional heat be added through the
13 evaporator, beyond that required only for evaporation of the
14 fluid. Because the geometry of the evaporator is restricted
15 because of limitations with respect to the capillary structure
16 and the desire to use LHP and CPL flight hardware, additional
17 heat input to the evaporator will result in increased
18 temperature gradients that will reduce the efficiency of the
19 overall system and could cause operation problems. The
20 preheater geometry can be designed to effectively accept a
21 portion of the required input heat transforming the working
22 fluid from a subcooled state to a saturated state allowing the
23 evaporator to operate more efficiently. For an isotope or
24 active nuclear space system, the preheater and superheater can
25 interface with the same heat source that drives the capillary
26 wick, however the superheater would receive higher temperature
27 heat. For satellites, the liquid preheater and evaporator could
28 be exposed to waste heat from the satellite electronics and the

1 superheater could be heated by solar energy. Heat input to the
2 superheater can be direct from a heat source or using thermal
3 energy storage. For a space-based application, the turbine can
4 have an electromagnetic coupling for eliminating leakage around
5 shaft seals. The superheated vapor drops in pressure as energy
6 is extracted. The flow will then enter the condenser where heat
7 will be transferred out to an external sink in the environment.
8 In practice, the condenser can be a tube that the cycle flow
9 passes through with several serpentine bends. This tube is
10 exposed to a cold heat sink. The cold heat sink will cause the
11 vapor to condense to liquid as the flow is forced through the
12 condenser tubes. The flow exits the condenser as saturated
13 liquid to enter the liquid pump where the pressure is increased
14 isentropically. High pressure, low temperature, subcooled
15 liquid leaving the pump enters the liquid preheater where heat
16 is added. The flow, high pressure, high temperature, saturated
17 liquid leaves the liquid preheater and enters the capillary
18 wick to repeat the cycle. The system provides two-phase
19 thermodynamic operation well suited for space-based
20 applications. These and other advantages will become more
21 apparent from the following detailed description of the
22 preferred embodiment.

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Brief Description of the Drawings

Figure 1 is a block diagram of a superheater power generating thermal cycle system.

Figure 2 is a temperature and entropy graph of a superheater power generating thermal cycle.

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Detailed Description of the Preferred Embodiment

An embodiment of the invention is described with reference to the figures using reference designations as shown in the Figures. Referring to Figure 1, a two-phase thermodynamic power system includes a capillary device, a superheater, an inline turbine, a condenser, a liquid pump and a liquid preheater for generating output power. The capillary device, such as a loop heat pipe or a capillary pumped loop, is coupled to an accumulator that is coupled to the superheater. The capillary device includes a capillary wick and a container, combined to make an evaporator. The capillary device is driven by a capillary heat source. The capillary device provides high-pressure saturated vapor through a high-pressure vapor path to a preferred vapor accumulator that is in turn connected to the superheater. The superheater includes a plurality of unidirectional diode valves, such as valves A, B, and C, that are respectively connected to a plurality of heating chambers, such as chambers A, B, and C, that are heated by a superheater heat source connected to a splitter for routing heat to the chambers. Each of the heating chambers are in turn respectively connected to control valves, such as control valves A, B, and C, that are controlled by a controller for staggered release of superheated vapor through a superheated vapor path to the inline turbine. The superheater is coupled to the inline turbine for generating output power as power out for operation as an electrical power generator. The low-pressure saturated vapor enters the superheater where it is superheated for

1 driving the turbine. When passing through the turbine, the
2 superheated vapor is cooled to low-pressure saturated pressure
3 vapor that is passed into a low-pressure saturated vapor path
4 connected to a condenser. Low pressure saturated vapor exiting
5 the turbine condenses to liquid in the condenser into low-
6 pressure saturated liquid and flows through a low-pressure
7 saturated liquid path. This low-pressure saturated liquid may
8 then be preferably pressurized while passing through a liquid
9 pump providing high-pressure, low temperature subcooled liquid
10 into a high-pressure, low temperature subcooled liquid path.
11 The high-pressure, low-temperature, subcooled liquid is then
12 heated in a liquid preheater provided high-pressure, high-
13 temperature saturated liquid to the capillary device completing
14 the cyclic path around the thermodynamic power system. The
15 capillary device receives input heat from the capillary heat
16 source and this heat is used to change the phase of the high-
17 pressure, high-temperature liquid into high-pressure saturated
18 vapor. The superheater isolates extremely high-pressure vapor
19 from the capillary device. The optional liquid pump isolates
20 extremely low pressure liquid from the capillary device
21 isolating either or both high and low cycle pressures from the
22 capillary device that allow the cycle to operate at differences
23 in pressure far greater than that which the capillary device
24 can sustain, for providing increased power output over the
25 power that can be provided by only the capillary device.

26
27 The system relies on a pressure difference generated
28 during the evaporation of the working fluid from a capillary

1 wick to create a high-pressure saturated vapor that is then
2 superheated for driving the turbine. Hence, the maximum power
3 production is not limited by the maximum capillary pressure
4 differential that can be sustained across the capillary wick.
5 The superheater is coupled through the flow of the working
6 fluid but decoupled with respect to pressure from the capillary
7 wick using unidirectional vapor valves such as the diode
8 valves. The capillary wick in the cycle provides the pressure
9 difference generated across the wick structure that is only
10 required to establish fluid flow through the accumulator and
11 into the superheater, while separating liquid from vapor. High
12 temperature heat energy input to the system preferably enters
13 through the superheater while low-temperature heat energy input
14 enters through the liquid preheater and evaporator.

15
16 In the superheater, the flow-pressure is significantly
17 increased through heat addition. This heat addition creates a
18 condition where the maximum pressure differential in the cycle
19 is the highest pressure out of the superheater minus the lowest
20 pressure of the low-pressure saturated liquid path. This
21 maximum pressure differential is far greater than the pressure
22 differential that the capillary wick can sustain. However, the
23 capillary wick is not subjected to this maximum pressure
24 differential because the capillary wick is isolated from the
25 pressure in the superheater by the diode valves. That is, the
26 efficiency and power production of the system is not limited to
27 only the pressure differential that the capillary device can
28 sustain. High-pressures generated in the superheater do not

1 affect the pressure in the high-pressure saturated vapor path
2 of the cycle because pressures in the superheater are isolated
3 from the saturated vapor path by diode valves. Under heat
4 addition, the pressure in the superheater increases to a
5 pressure level much higher than that in the high-pressure
6 saturated vapor line. Flow from the superheater is isolated by
7 the use of the diode valve on the saturated vapor side and is
8 released by the use of the control valves. When the pressure in
9 the pulse oscillating superheater reaches a predetermined
10 valve, the control valve is opened exposing the high-pressure
11 superheated vapor to the superheated vapor path that leads to
12 the turbine. The high-pressure superheated vapor travels
13 through the superheated vapor path to a turbine where power can
14 then be efficiently extracted. The flow from the turbine enters
15 the condenser, such as a radiator, where the low-pressure
16 saturated vapor condenses into liquid. The unidirectional flow
17 around the system is maintained but operating with
18 significantly increased pressure ranges, temperature ranges,
19 and power levels with improved efficiencies over simple
20 capillary pumped devices. The liquid pump and liquid preheater
21 are preferably added to further increase the operating range
22 and efficiency of the system.

23
24 A working fluid, such as ammonia or water obtains a liquid
25 phase and a vapor phase in the two-phase power generation
26 system. Starting at the saturated liquid path, high-pressure,
27 high-temperature saturated liquid moving along a high-pressure,
28 high-temperature saturated liquid path to the evaporator being

1 a capillary device having a capillary wick within a wick
2 container. The evaporator may be, for example, an evaporator
3 from a conventional loop heat pipe or a conventional capillary
4 pumped loop. Forced heat into the evaporator serves to drive
5 the capillary device. This high-pressure, high-temperature,
6 saturated liquid is pushed into the capillary wick under
7 pressure. The capillary wick provides the separation between
8 the high-pressure saturated vapor and the high-pressure, high-
9 temperature saturated liquid. Flow through the capillary wick
10 is achieved because the working liquid wets the capillary wick
11 as fluid molecules are attracted to the capillary wick more
12 than to each other to draw the working fluid through the
13 capillary wick. The fluid is also pushed through the capillary
14 wick from the pressure generated at the saturated vapor side of
15 the capillary wick, in the superheater and from the liquid
16 pump. Heat from the capillary heat source is fed into the
17 capillary wick that is further connected to the capillary
18 evaporator that is in turn connected to a high-pressure
19 saturated vapor path in which the working fluid is a saturated
20 vapor. Vaporization increases the volume and pressure of the
21 working fluid on the heated output side of the capillary wick.
22 The vapor pressure pushes the working fluid as high-pressure
23 saturated vapor forward through the high-pressure saturated
24 vapor path towards the vapor accumulator and superheater. Flow
25 backwards toward the saturated liquid path is blocked because
26 the pores in the capillary wick are so small that the working
27 fluid forms a meniscus in the capillaries. The meniscus serves
28 as a barrier to the high-pressure saturated vapor. The pressure

1 differential on opposing sides of the capillary wick is used to
2 provide flow through the accumulator to the superheater.

3
4 The high-pressure saturated vapor path flow is connected
5 to a superheater. The high-pressure saturated vapor is heated
6 by the superheater connected to a superheated vapor path that
7 connects to a turbine to produce power as work out. The vapor
8 flows from the superheater through the turbine, extracting work
9 and simultaneously lowering the pressure of the working fluid
10 flow that reaches the low-pressure saturated vapor point. The
11 superheater is a heat exchanger that may interface with the
12 capillary heat source and preheater heat source in any
13 combination or all heat sources can be separate. Heat sources
14 can be radioisotope, active nuclear, and or solar. The heat
15 source for the capillary device and liquid preheater is at a
16 lower temperature than the heat source for the superheater. The
17 heat source can include a thermal energy storage material such
18 as a salt or liquid metal that having a single phase or
19 multiple phases for providing heat during time of solar shade
20 as when in a low earth orbit, while the superheater heat source
21 is also a solar heat source for providing heat during times of
22 solar illumination. The heat source for the capillary device
23 and liquid preheater can be waste heat from a spacecraft or
24 waste heat rejected from another power system. The superheater
25 is preferably tubes with respective input diode valves and
26 output control valves. The working fluid flows through the
27 diode valves, into tubes that may have several serpentine
28 bends, and then through the control valves in an oscillating

1 manner having staggered releases of superheated vapor. The
2 working fluid flow exits the superheater as a superheated
3 vapor. The superheated vapor flows through the superheated
4 vapor flow path. The superheater adds heat to the working fluid
5 that ensures that no condensed liquid droplets enter the
6 turbine. Superheated vapor can prevent erosion of the turbine.
7 The superheated vapor path provides superheated vapor to drive
8 the turbine. The superheated vapor flow drops in pressure as it
9 flows through the turbine where energy is extracted in the form
10 of mechanical energy, through a shaft, not shown. This
11 mechanical energy can be used to perform useful work such as
12 work out for turning a generator to generate electrical power.
13 The low-pressure saturated vapor flow path is connected to the
14 low-pressure side of the turbine. The working fluid can be
15 nearly at saturation, slightly superheated or at a quality of
16 typically above 90% as it flows through the low-pressure
17 saturated vapor path out of the turbine. The low-pressure
18 saturated vapor path is connected to the condenser. The working
19 fluid flow will then enter the condenser from the low-pressure
20 saturated vapor path. In the condenser, the working fluid will
21 change phase, from a low-pressure vapor to a low-pressure
22 liquid. Heat will be transferred out to an external sink, such
23 as a radiator, in the environment as heat out. As the working
24 fluid flow passes through the condenser, the working fluid
25 undergoes a phase change from vapor to liquid. The condenser
26 can be a tube through which working fluid flow passes using
27 several serpentine bends. This tube is exposed to a cold heat
28 sink, such as outer space. The exit of the condenser is

1 connected to the low-pressure saturated liquid path. The
2 working fluid flows from the condenser through the low-pressure
3 saturated liquid path to an optional liquid pump. The liquid
4 pump increases the pressure of the flow. The flow exits the
5 pump through the high-pressure and low-temperature liquid path.
6 The flow then enters an optional liquid preheater. The liquid
7 pump and liquid preheater can be used to extend the performance
8 envelop of the power cycle. This allows for a broad choice of
9 operating fluids, power levels and boundary condition
10 temperatures. The liquid preheater adds heat to the flow to
11 increase the liquid temperature. The preheater can provide heat
12 from the same heat source as the superheater heat source or the
13 capillary heat source or the preheater can be heated from an
14 independent heat source. The flow then enters the high-pressure
15 and high-temperature saturated liquid path that is connected to
16 the capillary wick. The cycle is repeated as the working fluid
17 passes through the system for power generation.

18
19 Referring to the Figures, and particularly to Figure 2, the
20 thermocycle can also be described with respect to fluid
21 entropy. The working fluid preferably enters the capillary wick
22 at a high-pressure high-temperature saturated liquid point. The
23 liquid at the high-pressure high-temperature saturated liquid
24 point and the vapor at the high-pressure saturated vapor point
25 are completely separated during the heat addition to the
26 capillary wick. During heat addition, saturated liquid changes
27 directly to saturated vapor crossing the capillary interface
28 jump. Crossing the capillary interface causes the working fluid

1 to go directly from a saturated liquid to a saturated vapor
2 without a mixture of vapor and liquid occurring during the heat
3 addition process. That is, the capillary interface jump on the
4 temperature and entropy graph of Figure 2 mirrors the physics
5 at the liquid vapor interface of the capillary wick, where
6 lower-pressure liquid is physically in contact but separated
7 from higher-pressure vapor. That is, at the vapor-liquid
8 interface the liquid and vapor are in contact but separated.
9 After heat addition, the working fluid is at the high-pressure
10 saturated vapor point. The vapor is accumulated by the vapor
11 accumulator, during operation the accumulator dampens pressure
12 oscillations to the evaporator occurring from flow entering the
13 superheater in pulses. As flow leaves the high pressure
14 saturated vapor line and enters the superheater, flowing
15 through the diode valves, pressure in the high-pressure
16 saturated vapor line will momentarily drop. If this pressure
17 drop is large enough, it could affect the operation of the
18 evaporator. The accumulator effectively increases the overall
19 volume of the high pressure saturated vapor available to the
20 superheater and can be sized so that pressure oscillations are
21 minimized. The accumulated high-pressure saturated vapor from
22 the vapor accumulator flows into the superheater for
23 superheating to a superheated vapor point. The superheated
24 vapor at the superheated vapor point is passed through the
25 turbine that cools the superheated vapor to low-pressure
26 saturated vapor at the low-pressure saturated vapor point. The
27 low-pressure saturated vapor is passed through the condenser
28 that changes the phase by a condenser phase change of the

1 working fluid to a low-pressure saturated liquid at the low-
2 pressure saturated liquid point. The low-pressure saturated
3 liquid is pressurized to a subcooled state by the liquid pump
4 and becomes a high-pressure low-temperature subcooled liquid at
5 a high-pressure low-temperature subcooled liquid point. The
6 high-pressure subcooled liquid is then heated by the preheater
7 changing the flow into the high-pressure high-temperature
8 saturated liquid at the high-pressure high-temperature
9 saturated liquid point where the working fluid enters the
10 capillary wick, to complete the entropy cycle.

11
12 Referring to Figures, and particularly to the superheater,
13 the superheater is divided into parallel stages each having a
14 respective diode valve, chamber, and control valve. The
15 superheater can have as many stages as desired. For simplicity,
16 a two-stage superheater is described having chambers A and B.
17 Both chambers A and B are subjected to continuous steady state
18 heat input from the superheater heat source. At time equal to
19 zero, that is, $T=0$, the pressure in the superheater stage A is
20 low at P_{low} , the pressure in the superheater stage B is high at
21 P_{high} . At time $T=0$, the high-pressure saturated vapor flows into
22 chamber A and the control valve A is closed. The control valve
23 B for chamber B is then opened. When opened, high-pressure
24 superheated vapor is injected by pressure into the superheated
25 vapor flow path toward the turbine. At time equal to one, that
26 is, $T=1$, the pressure of chamber A reaches a pressure equal to
27 the pressure of the high pressure saturated vapor line pressure
28 P_{equal} . At time $T=1$ flow into chamber A stops, as the control

1 valve B for chamber B closes, and the pressure in chamber B is
2 now at P_{low} , and the saturated vapor flow begins to enter
3 chamber B. At time $T=2$, chamber A reaches the high-pressure
4 P_{high} , and the control valve A is opened exposing high-pressure
5 superheated vapor to the superheated vapor path toward the
6 turbine. Flow again travels through the superheated vapor path
7 toward the turbine. When the pressure in chamber B reaches
8 P_{equal} where superheated vapor flow in stops and the control
9 valve B remains closed. At time three $T=3$, the two chambers A
10 and B reach the same pressure as at time $T=0$, to complete the
11 staggered pulsed cycling of the superheater. It should now be
12 apparent that the flow from the superheater is staggered in
13 pulse from the plurality of the chambers. It should further be
14 apparent that other types of multiple stage superheaters could
15 be used, such as inline superheaters using cascaded chambers
16 operating in incremental predetermined temperature valves, but
17 still having pulsed injection of incremental amounts of
18 superheated vapor toward the turbine.

19
20 The high-pressure saturated vapor path from the capillary
21 device is preferably connected to the vapor accumulator.
22 Saturated vapor flows out of the vapor accumulator to the
23 superheater. The vapor accumulator is an empty pressure vessel
24 so that vapor can enter the superheater in mass flow pulses.
25 The function of the vapor accumulator is to isolate the
26 capillary evaporator from vapor mass flow pulses caused by the
27 vapor flow stopping and starting at the superheater entrance of
28 the unidirectional diode valves. These mass flow pulses could

1 have an adverse effect on the ability of the capillary
2 evaporator to maintain separation of vapor and liquid. These
3 pulses could also cause a reduction in the temperature of the
4 saturated vapor exiting the capillary evaporator. The volume of
5 the vapor accumulator is such that vapor mass flow pulses
6 induced at the superheater entrance will be dampened a
7 sufficient amount so that there will be no adverse effect from
8 these pulses on the capillary evaporator.

9
10 The saturated low-pressure liquid path is connected to a
11 liquid pump. Liquid flows out of the liquid pump through the
12 subcooled high-pressure low-temperature liquid path. The liquid
13 pump can be a conventional terrestrial two-phase power cycle
14 pump and be capable of increasing the pressure of the liquid by
15 several hundred pounds per square inch. The liquid pump
16 requires electric power input. A liquid pump in cycle is
17 operated to increase the pressure of the working fluid liquid
18 prior to entering the capillary evaporator. By increasing the
19 pressure before entering the capillary evaporator, the pressure
20 difference between the saturated high-pressure high-temperature
21 liquid entering the evaporator and the high-pressure saturated
22 vapor leaving the evaporator can be minimized while the
23 saturated low-pressure liquid pressure in the condenser is
24 chosen for optimum cycle efficiency. Using a liquid pump allows
25 for increased cycle efficiency by enabling a lower operating
26 temperature in the condenser.

1 The liquid preheater is connected to the subcooled high-
2 pressure low-temperature subcooled liquid path from the liquid
3 pump. Liquid flows out of the liquid preheater into the
4 saturated high-pressure high-temperature saturated liquid path
5 towards the capillary wick. The liquid preheater can be a
6 hollow tube that interfaces with a preheater heat source to
7 allow for heat addition. The preheater heat source is attached
8 to the liquid preheater tube. The heat source can be waste heat
9 from a spacecraft, solar energy, or nuclear energy. The heat
10 source for the liquid preheater can be the same as or separate
11 from the heat source for the capillary evaporator or the
12 superheater.

13
14 With a liquid pump incorporated into the power cycle, low
15 operating temperatures, just above the freezing point of the
16 working fluid, are possible in the condenser. After this cold
17 fluid from the condenser passes through the liquid pump, it is
18 significantly subcooled. If this fluid were returned directly
19 to the evaporator without passing through the liquid preheater,
20 a significant amount of additional heat would need to be added
21 through the evaporator, beyond that required only for
22 evaporation of the fluid. This significant amount of added heat
23 may adversely affect the performance of the capillary
24 evaporator by requiring a significantly higher temperature for
25 heat input to the evaporator. Adding the liquid preheater to
26 the cycle allows for the liquid to be preheated prior to
27 entering the evaporator which enables the evaporator to operate

28

1 at high efficiency while the power cycle operates over an
2 extended temperature range.

3
4 The thermodynamic power system is well suited for a
5 variety of space applications such as a primary power system
6 using a radioisotope, active nuclear, waste heat, and/or solar
7 energy as a heat source. These heat sources are useful for
8 heating the liquid preheater, the capillary wick and the pulse
9 superheater and driving the working fluid flow for increased
10 power efficiency and lifetime operation. The power system is
11 well suited for space receiving heat from a heat source to
12 produce useful mechanical energy. The two-phase thermodynamic
13 power cycle provides improved efficiency of over 30% while
14 operating at a maximum temperature of 637.4K. The system yields
15 a power converter that is efficient while operating at
16 relatively low maximum temperatures. Also, because the heat
17 addition process occurs at varying temperatures, low-grade
18 waste can be used to supplement the energy heat source
19 requirements. Those skilled in the art can make enhancements,
20 improvements, and modifications to the invention, and these
21 enhancements, improvements, and modifications may nonetheless
22 fall within the spirit and scope of the following claims.